Some unresolved problems of star formation and their relevance to Suffa project

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Introduction

Construction of a giant 70-m radio telescope, whose operating wavelength range was supposed to reach $\lambda \sim 1$ mm, began on the Suffa plateau back in the 1980s (Hojaev and Shanin, 1997; Hojaev et al., 2007; Artemenko et al., 2019). The construction was frozen in the 1990s, but there are plans to resume it.

Alternative plans to build one or more smaller antennas at the site are also being considered.

Aims

Study of star formation(SF) will be one of the priority tasks for the RT70-Suffa

- we should learn more on of the morphologic structure and kinematics of SF regions to better understand the SF process;
- study young stars' (or their circumstellar envelopes', accretion and protoplanetary disks') emission in millimeter wave ;
- search for new cores and clumps in SF molecular clouds as progenitor cores or possible pre-protostars and protostars ;
- joined analysis of physical properties and kinematics of PMS stars, YSO, dense prestellar cores and clumps using simultaneously the observations in optics, mm-wave and other ranges using the data of Gaia EDR3, 2MASS, Chandra, Spitzer, IPHAS etc.;
- determination of total and local [including dense cores and clumps] mass, density, temperature, rotation parameters, chemistry or molecular content, etc. of molecular clouds [especially the Giant Molecular Clouds] and their systems in the Galaxy and other galaxies to estimate the probability of SF, construct their dynamical models and consider their impact onto the galaxy structure and dynamics

Some unresolved problems of Star Formation

- How do massive stars form?
- What are the initial conditions for the formation of star clusters?
- How do molecular clouds form?
- Are molecules needed to form stars?
- What causes turbulence?
- What triggers/regulates star formation on a galactic scale?7
- How does star formation depend on metallicity?
- What is the role of massive stars in stimulating or suppressing the formation of future generations of stars?
- Are Hub-filament systems (HFSs) potential sites for the formation of star clusters and massive stars?
- What is the evolutionary relationship between hot cores, hypercompact, and ultracompact H II regions—do they represent successive stages in the evolution of the region around a massive young star?
- Is there or is there no dust in the compact regions of the ionized hydrogen around young stars?
- What stages of evolution of YSOs are accompanied by the appearance of maser emission?
- Where does the maser emission form in relation to a YSO?

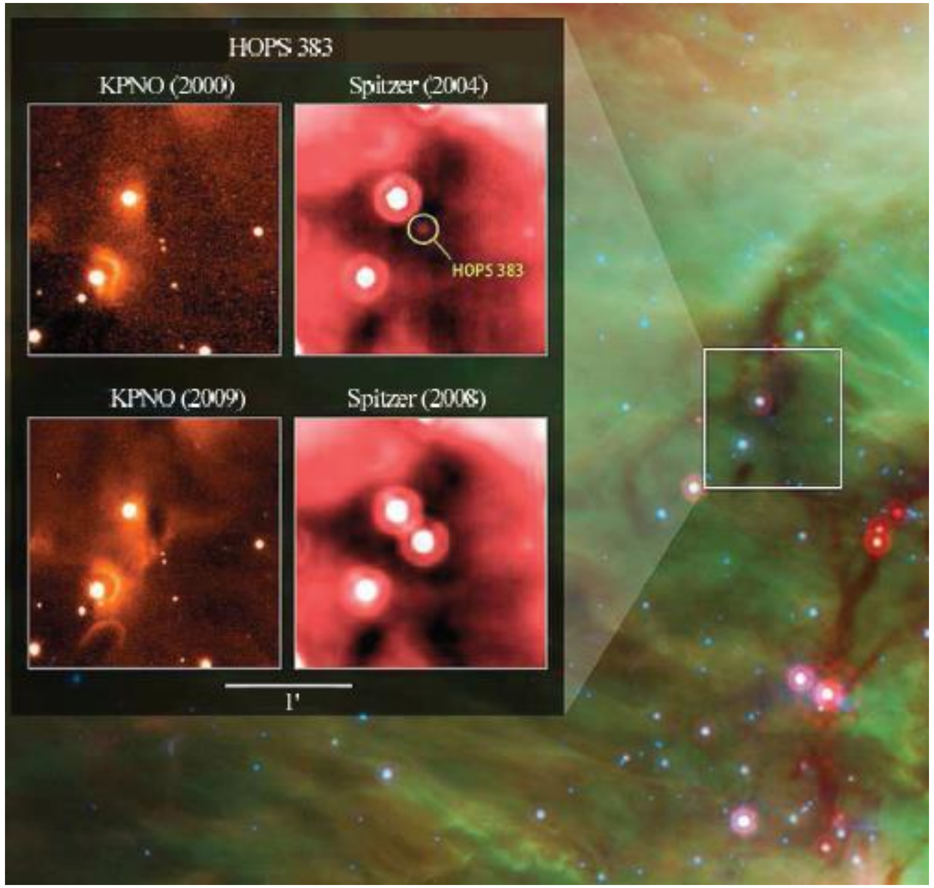
Actions to resolve at least some of the issues raised

1) to identify large-scale structures (filaments) in which stars form and study their properties;
2) to study the physical properties (temperature, density), chemical stratification in clouds resulting from the action of radiation fields (PDRs), and kinematics (the velocity distribution);
3) to detect molecules (including organics) in the diffuse interstellar gas;
4) to identify new protostars and young objects for subsequent studies of their physical structure;
5) to study the influence of the environment on SF, to determine the efficiency and rate of SF, and to answer all questions related to the fragmentation process and IMF;
6) to identify objects for further research of their physical structure;
7) to clarify the details of angular momentum and magnetic flux loss.

Target selection principles

There are a number of cells and large SF regions in our Galaxy, where active star formation is observed and where there are many protostars. However, our goal is to limit ourselves to the region of the celestial sphere accessible from the latitude of the IRAO “Suffa”, which is mainly its Northern hemisphere. Therefore, we have made a selection of these intensively studied, but nevertheless requiring more detailed study objects.

It should be taken into account here that in winter, the Suffa plateau has more favorable conditions for observations due to the greater transparency of the atmosphere in the millimeter range (and, there-fore, the best limiting or minimum flux that can be detected from the source), associated with the minimum value of the precipitable water vapor (PWV) (see, for example, Hojaev et al., 2007; Bubnov et al., 2017; Zinchenko et al., 2023). Therefore, “winter” objects will have advantages and priority in identifying the weakest objects in the SF regions.



HOPS 383 in the Orion SF region.

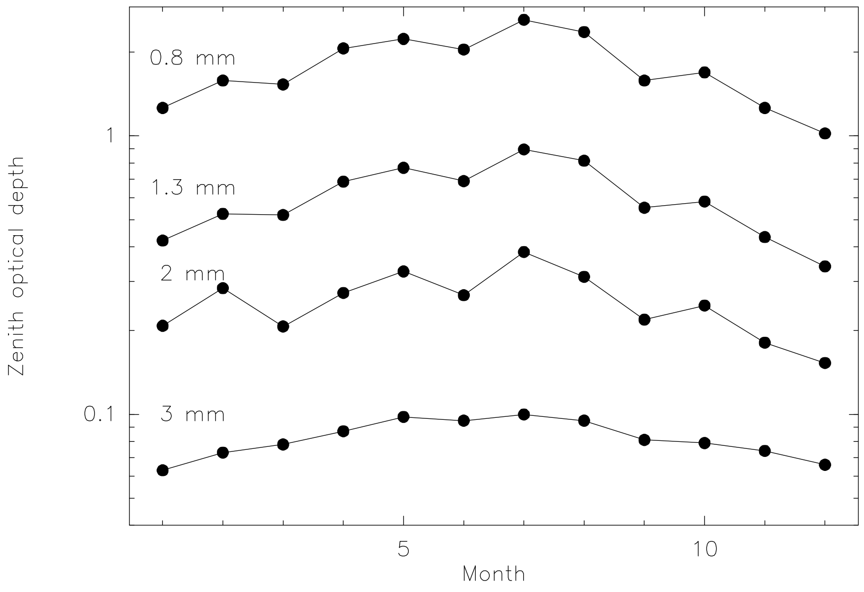
Perspective targets

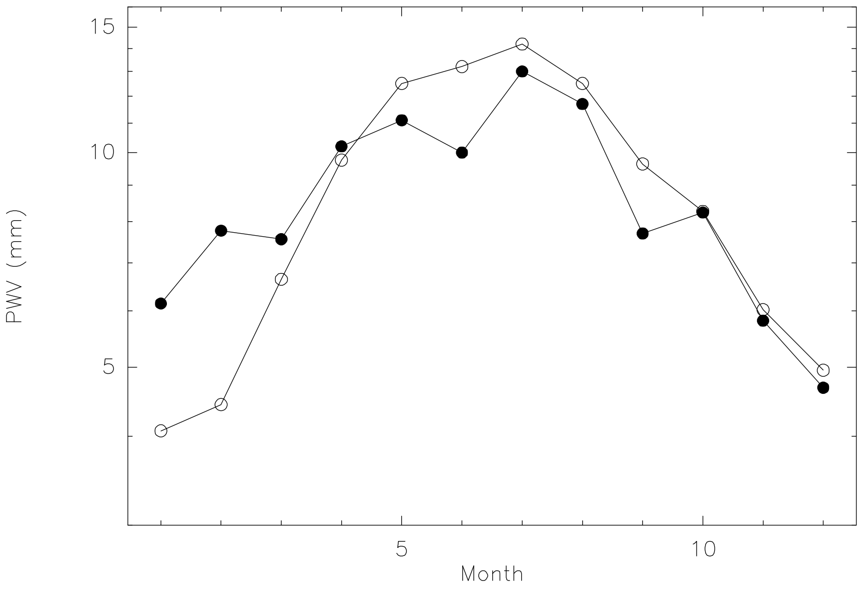
No.	Name	RA (J2000)	Dec (J2000)	d, pc
1	NGC 1333	$03^h\ 29^m\ 11^s.3$	$+31^\circ\ 18'\ 36''$	325
2	Perseus (Per MCld)	$03^h\ 35^m\ 00^s.0$	$+31^\circ\ 13'\ 00''$	307
3	NGC 1499	$04^h\ 03^m\ 18^s.0$	$+36^\circ\ 25'\ 18''$	300
4	Taurus	$04^h\ 41^m\ 00^s.0$	$+25^\circ\ 52'\ 00''$	140–145
5	Orion (M 42)	$05^h\ 35^m\ 17^s.3$	$-05^\circ\ 23'\ 28''$	412
6	Monoceros (NGC 2264)	$06^h\ 41^m\ 00^s.0$	$+09^\circ\ 53'\ 00''$	720
7	Ophiuchus (S 1 в ρ Oph)	$16^h\ 28^m\ 06^s.0$	$-24^\circ\ 32'\ 30''$	140
8	Aquila (M 16)	$18^h\ 18^m\ 48^s.0$	$-13^\circ\ 49'\ 00''$	1700
9	Omega Nebula (M 17)	$18^h\ 20^m\ 26^s.0$	$-16^\circ\ 10'\ 36''$	1700
10	W40 (Sharpless 64)	$18^h\ 31^m\ 29^s.0$	$-02^\circ\ 05'\ 24''$	436
11	W43	$18^h\ 47^m\ 32^s.4$	$-01^\circ\ 56'\ 31''$	5500
12	W49	$19^h\ 10^m\ 17^s.0$	$+09^\circ\ 06'\ 00''$	11 100
13	Vulpecula	$19^h\ 44^m\ 00^s.0$	$+24^\circ\ 13'\ 00''$	1600
14	Cygnus X	$20^h\ 20^m\ 00^s.0$	$+40^\circ\ 00'\ 00''$	1500
15	AFGL 2591	$20^h\ 29^m\ 24^s.9$	$+40^\circ\ 11'\ 19''$	3400
16	Pelican Nebula	$20^h\ 50^m\ 48^s.0$	$+44^\circ\ 20'\ 60''$	550
17	NGC 7000	$20^h\ 59^m\ 17^s.1$	$+44^\circ\ 31'\ 44''$	800
18	Cepheus	$22^h\ 29^m\ 00^s.0$	$+56^\circ\ 36'\ 00''$	3400

Atmospheric Transparency at Millimeter Waves on the Suffa Plateau

At the RT-70 construction site @ Suffa plateau, atmospheric absorption has been monitored since 2014 in the 3 and 2 mm wavelength ranges using a specialized dual-band radiometer developed at the IAP RAS (Bubnov et al., 2017). The results of monitoring in the 2 mm wavelength range are in good agreement with absorption estimates from the global atmospheric model and with data on the PWV content in the atmosphere (Bubukin et al., 2023).

Overall, these results show that regular effective radio astronomical observations at wavelengths up to 2mm are possible at this site. At shorter wavelengths, only occasional observations are possible mainly in winter.





(Bubnov et al., 2017)

Observational capabilities - Radio telescope RT-70 Suffa

Hojaev and Zinchenko,2021 showed that it will take about 10 minutes to obtain a complete (according to Nyquist) map of 1 arcmin^2 area, taking into account calibrations and pointing checks at a sensitivity of ~0.3 K (in the brightness temperature scale) at a resolution of 1 km/s and beam efficiency of 0.5 in the wavelength range of 3 mm. Such sensitivity will make it possible to observe relatively strong lines with the brightness temperature $T_b \sim 1$ K, such as, for example, the lines of the CO, ^{13}CO, $C^{18}O$, CS, HCN, HCO^+, and other molecules. A spectral resolution of 1 km/s will allow measuring the integral intensity of lines, but it is insufficient for studying the features of line profiles (for example, self-absorption details). In dark cold clouds, the line width may be noticeably smaller than 1 km/s. To detect them, a higher resolution should be used. We consider only the 3mm wavelength range, since at shorter wavelengths, the efficiency of the 70-m antenna will probably be rapidly lost.

The expected beam width of the RT-70 at half intensity at this wavelength is ~ 10”. The mapping of the 20’ × 20’ area will take about 70 hours. These estimates are made for a single-beam receiver. For studies of the extended sources, matrix receivers with a large number of elements can be used, which, accordingly, allows one to reduce the observation time. At the same time, the optical scheme of the telescope must provide a sufficiently large field of view. This approach is implemented, for example, in the CCAT/FYST projects (Stacey et al., 2022; Aravena et al., 2023) and AtLAST (Klaassen et al., 2020). The optical scheme of the RT-70 also provides for a fairly large field of view. It should be noted, however, that so far only bolometer matrices with a very large number of elements (~ 10^4) have been created. The development of matrix heterodyne receivers with a number of elements greater than 10 is a very complex and as yet unsolved technical problem.

Observational capabilities - small-size mm/submm telescopes

Due to the difficulties with completing the construction of RT-70, the construction of an antenna with a diameter of 15–20 m is considered. The source mapping speed, while maintaining the requirements for brightness temperature sensitivity and with the same main beam efficiency, increases proportionally to the main beam solid angle. Thus, for an antenna with a diameter of 20 m, it will be approximately an order of magnitude higher than for a 70-m antenna. But of course, the angular resolution in the resulting map will be approximately three times worse. Despite this, such an antenna will allow solving most of the scientific problems considered for a 70-m antenna, with the exception of studying compact structures (for example, dense cores in molecular clouds), due to the angular dimensions of which a larger antenna is required.

But at the same time, with such an antenna it will be easier to implement observations at shorter waves, which will improve the angular resolution, and will also provide the opportunity to observe additional transitions of various molecules, which is important for analyzing the physical conditions in the sources. It is also assumed that such an antenna will operate in the VLBI mode together with other similar antennas on the territory of the Russian Federation (see, for example, Stolyarov et al., 2024).

Observational capabilities - mm/submm telescopes' array

Another possible option is to build an interferometer from relatively small (3–8 m in diameter) antennas. The sensitivity of one element of the interferometer is usually characterized by the System Equivalent Flux Density (SEFD):

$$\mathrm{SEFD} = \frac{2kT_{\mathrm{SYS}}}{A_{\mathrm{eff}}}$$

where T_{SYS} is the system noise temperature, A_{eff} is the effective antenna area, k is the Boltzmann constant. Assuming $T_{SYS} \sim 100$ K and the aperture efficiency of about 0.7, we get SEFD from 8000 to 60 000 Jy. For a system of 10 antennas, the expected sensitivity with the resolution of 1 km/s at a wavelength of 3 mm will be 2–10 Jy/beam with an integration time of 1 s. With the expected baseline of the antenna array of several hundred meters, the angular resolution at this wavelength will be 2”−3”. With this resolution, the brightness temperature sensitivity will be no better than 30 K in an integration time of 1 s. A sensitivity of 0.3 K assumed above can be achieved in a time of about three hours.

At the same time, the width of the primary beam pattern of one antenna will be 90”−230” and information will be obtained in this entire area simultaneously. The mapping of the 20’ × 20’ area will require several months. It should also be noted that the interferometer is not sensitive to the extended radiation on scales of about and more λ/D_{min}, where D_{min} is the minimum projection of the base between the antennas. In the case under consideration, the largest angular scale will be of the order of an arc minute.

It should be noted that bolometer matrices are not used with interferometers and, therefore, high-sensitivity continuum observations including polarimetry are possible only with a very wide reception band of heterodyne receivers (which is currently feasible). In general, such an antenna array is more suitable for detailed studies of relatively compact regions in extended clouds than for mapping such clouds entirely.

Discussion

The SF regions described above are very diverse, and contain a large number of objects at different stages of evolution. Detailed studies of these regions will allow significant progress in solving the problems listed in Slides 4-6. The sizes of most of these regions are very large. Observing them in their entirety with high resolution (for example, as expected for a 70-m antenna) and at the same time with high sensitivity to brightness temperature is practically impossible, since it would require a very long time. The optimum strategy seems to be mapping with a relatively low angular resolution and further studies of selected areas with higher resolution. The resolution requirements depend on the tasks and the type of object under study. One arc second corresponds to a linear size of about 1000 AU at a distance of 1 kpc and about 100 AU at a distance of 100 pc. The angular resolution of 10 mas achieved by ALMA allows detailed study of protoplanetary disks located at distances of about 100 pc (see, for example, Brogan et al., 2015), and the close vicinity of massive protostars at distances of several kiloparsecs (see, for example, Zinchenko et al., 2024). At the same time, quite competitive results are obtained using a submillimeter array (SMA) which has an angular resolution worse by more than an order of magnitude (see, for example, Zinchenko et al., 2012, 2015). The submillimeter array consists of eight antennas with a diameter of 6 m with a maximum base of about 500 m; something similar, in principle, could be implemented at the IRAO “Suffa”. The VLBI methods are used to study maser sources, in particular at ground-space baselines. The IRAO “Suffa” should be able to participate in such experiments jointly with the “Millimetron” planned space observatory (Novikov et al., 2021).

Discussion

For the efficient operation of any future observatory instrument, it is necessary to provide the widest possible reception band. This will allow receiving a large number of spectral lines simultaneously and achieving high sensitivity in the continuum. A large number of lines is important not only for astrochemical studies but also for assessing the physical parameters of sources. Modern technologies allow one to realize reception bands of about 30 GHz, which makes it possible to simultaneously observe the most important lines in a 3- or 2-mm transparency window of the atmosphere. To study the magnetic field, it is important to have the possibility of polarization measurements.

In general, any of the considered options for a millimeter telescope on the Suffa plateau will be competitive at the global level and will give the project participants the opportunity to develop the corresponding scientific directions.

Conclusions

Despite the significant progress achieved to date in the study of SF processes, many fundamental questions remain unresolved.

Objects accessible for observation on the Suffa plateau that can be used to solve these problems are described.

The capabilities of various instruments that could be built on this site were analyzed. Among them, there are: a 70-meter antenna, the construction of which was started many years ago but has not yet been completed; a smaller diameter antenna of 15–20 m; an antenna array consisting of smaller antennas.

The sizes of most SF regions proposed for study are quite large. The optimum strategy seems to be to map them with a relatively low angular resolution and then study the selected areas with higher resolution.

The creation of any instrument considered will contribute to the development of the corresponding scientific directions and will allow us to obtain important astrophysical results.